

3. Accuracy Requirements

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Satellite and surface measurements, if they are to serve as a climate monitoring system, must be accurate enough to permit detection of changes of climate parameters on decadal time scales. The accuracy requirements are difficult to define *a priori* since they depend on unknown future changes of climate forcings and feedbacks. As a framework for evaluation of candidate Climsat instruments and orbits, we estimate the accuracies that would be needed to measure changes expected over two decades based on theoretical considerations including GCM simulations and on observational evidence in cases where data are available for rates of change.

One major climate forcing known with reasonable accuracy is that caused by the anthropogenic homogeneously mixed greenhouse gases (CO_2 , CFCs, CH_4 and N_2O). Their net forcing since the industrial revolution began is about 2 W/m^2 (Fig. 2.2), and it is presently increasing at a rate of about 1 W/m^2 per 20 years (Hansen and Lacis, 1990). Thus for a competing forcing or feedback to be important, it needs to be of the order of 0.25 W/m^2 or larger on this time scale.

The significance of most climate feedbacks depends on their sensitivity to temperature change. Therefore we begin with an estimate of decadal temperature change. Figure 3.1 shows the transient temperature trends simulated by the GISS GCM when subjected to various scenarios of trace gas concentration increases (Hansen *et al.*, 1988). Scenario B, which represents the most plausible near-term emission rates and includes intermittent forcing by volcanic aerosols, yields a global mean surface air temperature increase $\Delta T_s = 0.7^\circ\text{C}$ over the time period 1995-2015. This is consistent with the IPCC projection of about $0.3^\circ\text{C}/\text{decade}$ global warming (IPCC, 1990). Several of our estimates below are based on this assumed rate of warming.

Climate Forcings

Ozone. Ozone changes have the potential to be a major climate forcing, for which rates of change can be estimated from recent observations. Change of total column ozone during the 1980s was monitored by the TOMS satellite instrument (Fig. 3.2; Stolarski *et al.*, 1991). But, as indicated

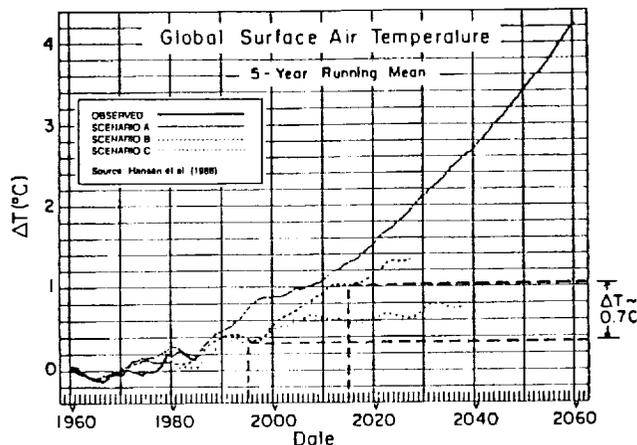


Fig. 3.1. Simulated global temperature change in climate simulations of Hansen *et al.* (1988). Rate of warming in the most realistic scenario (B), about $0.3^\circ\text{C}/\text{decade}$, is typical of other GCM and IPCC (1992) estimates.

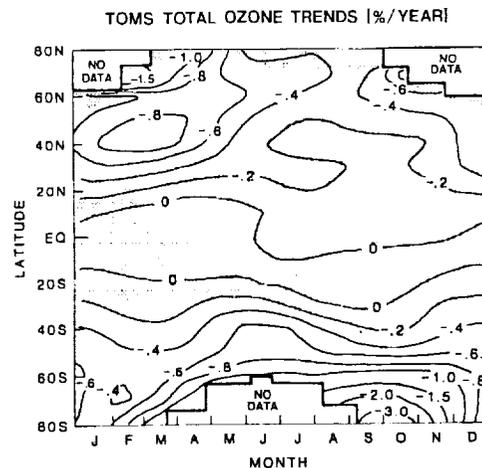


Fig. 3.2. Satellite (TOMS) observations indicate significant rate of total column ozone change during the 1980s (Stolarski *et al.*, 1991).

above (Figs. 2.2 and 2.3), the climate forcing due to the ozone change is entirely dependent on the vertical distribution of the ozone change. Data from a few mid-latitude ground stations suggest that the largest changes in the 1970s were near the tropopause (Fig. 2.4), and SAGE data for the 1980s suggest a qualitatively similar conclusion (McCormick *et al.*, 1992). The climate forcing by ozone depends mainly on the temperature of the ozone; as a result, it is required that the altitude of any significant ozone change be known within about 2 km in the troposphere and 5 km in the stratosphere. The magnitude of ozone change required to be significant is least at the tropopause, where changes of a few percent per decade are important, and increases toward both higher and lower altitudes.

Stratospheric water vapor. Doubling of stratospheric water vapor has been calculated to lead to a surface warming of the order of 1°C (Wang *et al.*, 1976), corresponding to a forcing of the order of 1 W/m². Thus, if the long-term change of stratospheric water vapor is monitored to a precision of 10 percent, its climate forcing can be defined very accurately.

Tropospheric aerosols. Tropospheric aerosols are thought to contribute substantially to climate forcing, but the magnitude of their impact is highly uncertain due to an absence of adequate global observations. Both anthropogenic and biogenic aerosols have received attention for their possible roles in climate change. Anthropogenic SO₂ emissions have probably at least doubled the sulfate aerosol concentration of the atmosphere over the past century relative to the background natural concentration (Fig. 3.3; Charlson *et al.*, 1992). Global increases of 10–20%, and regional increases of 50% or more, over a 20-year period are plausible. Such global aerosol changes could cause a direct aerosol forcing conceivably as large as 0.5 W/m², depending on the aerosol single scatter albedo, which would be comparable in magnitude to the expected climate forcing by anthropogenic greenhouse gases. Significant climate forcing from smoke due to biomass burning must also be considered (Penner *et al.*, 1992).

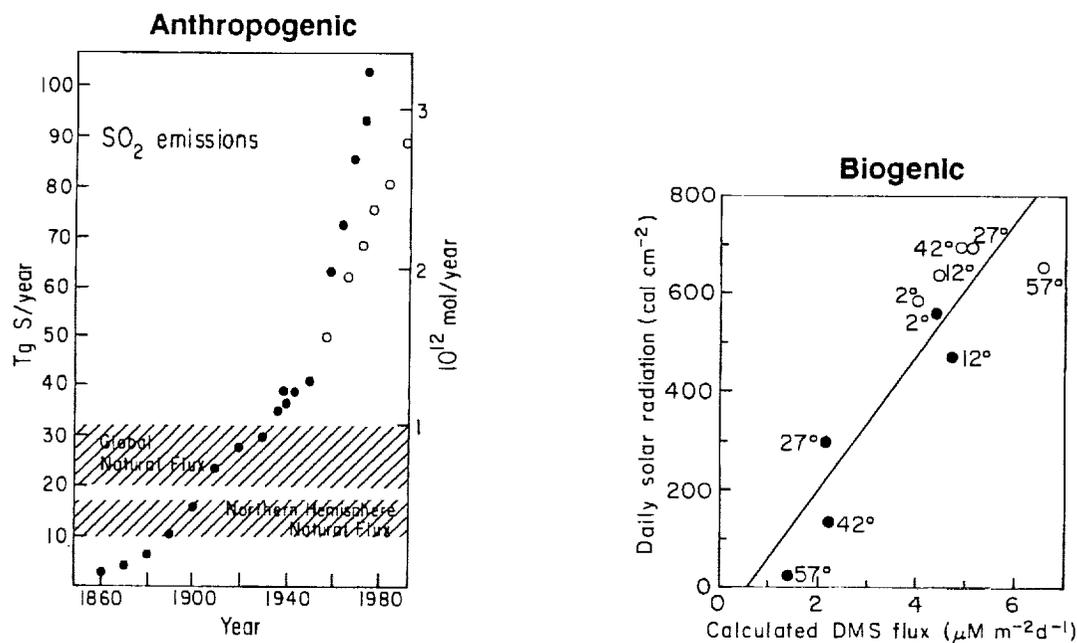


Fig. 3.3. Anthropogenic SO₂ emissions have probably at least doubled the sulfate aerosol concentration as evidenced by the above estimates for changes of SO₂ emissions. Open and filled circles represent data from two different sources (Charlson *et al.*, 1992).

Fig. 3.4. Biogenic DMS emissions are sensitive to solar irradiance as evidenced by observed correlations between surface insolation and oceanic DMS flux (Bates *et al.*, 1987).

Biogenic emissions of dimethylsulphide (DMS) from the ocean appear to be sensitive to surface solar irradiance (Fig. 3.4; Bates *et al.*, 1987). Given the magnitude of measured solar luminosity variations (much less than one percent; Willson and Hudson, 1988) and the small variations in cloud cover and optical properties simulated by climate change models (Schlesinger and Mitchell, 1987), associated aerosol changes would be limited to a few percent over 20 years, much less than the anthropogenic component (Foley *et al.*, 1991). However, DMS emissions may also depend on other variable climate parameters, e.g., surface wind speed, in ways not currently documented. Climate forcing by a given aerosol optical depth is greater over the lower albedo ocean than over land; a change of global ocean aerosol mean optical depth of 0.01 is climatically significant (global forcing $\sim 0.25 \text{ W/m}^2$). This change is an order of magnitude smaller than the accuracy or precision attainable with present satellite data.

The climate forcing by tropospheric aerosols depends on the aerosol optical depth, refractive index and size distribution, i.e., it is necessary to determine the aerosol microphysical properties (Patterson *et al.*, 1977; D'Almeida, 1987; Fouquart *et al.*, 1987; Tanre *et al.*, 1988; Leaitch and Isaac, 1991). A crucial parameter, which is very difficult to measure, is the aerosol single scatter albedo. One approach would be to infer the single scatter albedo by measuring the change of reflectance and aerosol optical depth together. The single scatter albedo needs to be known to an accuracy 0.02-0.03, which requires precision of the reflectance of the order of 0.01. Attainment of adequate knowledge of aerosol properties will require the combination of global satellite measurements supplemented by surface and in situ measurements for ground truth, as well as three-dimensional aerosol modeling.

Another major issue related to tropospheric aerosols is the changes which they may induce in cloud cover and cloud reflectivity. As an essential requirement for quantifying this climate forcing, the geographical distribution of aerosol microphysical properties must be monitored along with the cloud optical properties. The accuracy requirements for the measurements of cloud properties are described below.

Stratospheric aerosols. The climate forcing by stratospheric aerosols depends mainly on the visible optical depth of the aerosol layer, and secondarily on the aerosol size (Lacis *et al.*, 1992). Unlike the situation for the tropospheric aerosols, the forcing is practically independent of the amount of absorption by the aerosols (Lacis *et al.*, 1992). Addition of a visible optical depth of 0.15 causes a forcing of about 4 W/m^2 , approximately the same as that for doubled CO_2 , but in the opposite sense. Thus a significant climate forcing, 0.25 W/m^2 , is caused by an optical depth of 0.01, which defines the required measurement accuracy. The effective radius of the aerosol size distribution needs to be known within about 50 percent.

Solar irradiance. A solar irradiance change of 2 percent, if spectrally flat, causes a climate forcing of $4\text{-}5 \text{ W/m}^2$, roughly equivalent to doubled CO_2 . Thus a significant climate forcing would be produced by a solar irradiance change of about 0.1 percent, which defines the accuracy requirement for the integrated solar irradiance. However, climate forcing can also be caused by a change of the spectral distribution of the incoming radiation. The accuracy requirements are difficult to specify, because a change of the spectrum affects not only the amount and location of absorbed solar energy, but also may alter atmospheric composition, for example, ozone. The accuracies expected for the two spectral instruments on UARS, which monitor the sun in the ultraviolet region where the principal changes are known to occur, are probably sufficient, but measurements need to be extended to decadal time scales.

Surface reflectivity. A mean land reflectivity change of 0.1 is required to yield a forcing equivalent in magnitude to that for doubled CO_2 (Hansen *et al.*, 1988). Thus a significant global climate forcing (0.25 W/m^2) could result from a long-term mean surface reflectivity change of about 0.006. Since the mean land surface reflectivity is about 0.2, the long-term precision needed for surface reflectivity monitoring is about 2 percent.

Climate Feedbacks

Water vapor. The single largest positive feedback in GCM estimates of climate sensitivity is due to water vapor, the water vapor concentration increasing as climate warms. Climate models with a variety of approaches to the parameterizations of moist convection and stratiform clouds agree that *relative* humidity changes in a warming climate will be small, of the order of a few percent (Cess *et al.*, 1990; DelGenio *et al.*, 1991; Fig. 3.5). This implies large changes of *specific* humidity, i.e., water vapor concentration. Like ozone and clouds, though, the vertical distribution of the change is also important (Arking, 1993). Indeed, Lindzen (1990) has speculated that changes in moist convection in a warming climate could actually dry the upper troposphere enough to eliminate or reverse the water vapor feedback. Although, as discussed in Section 2, a broad range of scientific evidence argues against the extreme proposition of Lindzen, this does not reduce the need to better quantify the nature of the water vapor feedback by means of long-term monitoring of the change of the water vapor profile.

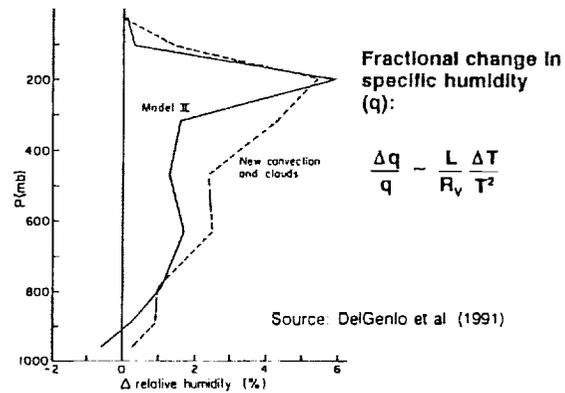


Fig. 3.5. Climate models with different approaches to the parameterization of convection and large-scale clouds yield similar responses of the water vapor profile to a change in surface temperature (DelGenio *et al.*, 1991).

If relative humidity changes are small, the Clausius-Clapeyron equation of thermodynamics can be used to estimate the change in specific humidity q from the change in saturation vapor pressure. The fractional change is $\Delta q/q \approx L\Delta T/(R_v T^2)$, where L is the latent heat of condensation, R_v the gas constant for water vapor, and T the temperature. For an assumed 0.7°C warming over 20 years, water vapor concentration would be expected to increase by about 4% (0.75 g/kg) near the surface and about 10% (0.001 g/kg) near the tropopause. Such a change of the water vapor profile, with everything else held fixed, would alter the net radiative flux at the tropopause or the top of the atmosphere by about $0.5\text{--}1.0 \text{ W/m}^2$, as indicated in Table 3.1.

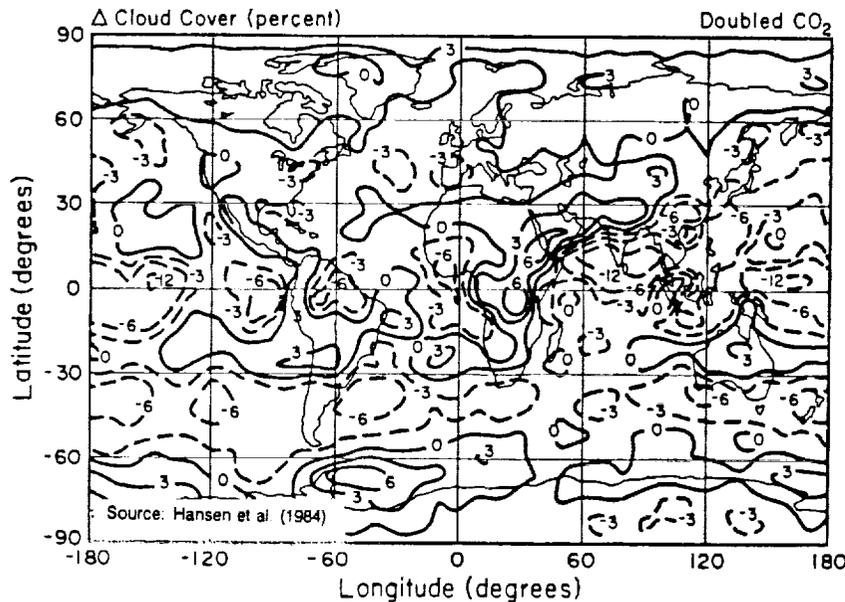


Fig. 3.6. Cloud cover changes in a doubled CO_2 experiment with the GISS GCM (Hansen *et al.*, 1984).

Cloud cover. There is no fundamental understanding of whether cloud cover should increase or decrease as climate warms, since the change depends on the subtle balance between the competing effects of moisture and temperature changes. Nonetheless, virtually all of the available GCMs which have been subjected to either doubled CO_2 (cf., Schlesinger and Mitchell, 1987) or a prescribed sea surface temperature anomaly (Cess *et al.*, 1990) predict that total cloud cover will slightly decrease as climate warms. The resulting cloud feedback on temperature is difficult to predict, because changes may be different for various cloud types, solar zenith angles, and underlying surface albedos. Simulated regional cloud changes are much larger than the global mean variation and may be of either sign (Fig. 3.6). Current GCMs suggest that over a 20-year period, global cloud amount may change by a fraction of a percent, with increases or decreases of 2-5% in different locations.

Ground-based observations of cloud cover (Henderson-Sellers, 1986, 1989; Karl and Steurer, 1990) suggest substantially larger variations over the past several decades, but the uncertainty in these observations is difficult to quantify. Satellite cloud observations (Rossow and Schiffer, 1991) show interannual global cloud changes of the order of a percent. A typical radiative flux change at the top of the atmosphere for a cloud cover change of 0.01 is 0.25 W/m^2 (Table 3.1) which is another indication of the cloud cover accuracy desired of observations.

Cloud height. All presently available GCMs predict that the mean altitude of cloud tops will rise in a warmer climate (Fig. 3.7). There are several physical processes which influence the vertical distribution of clouds. In the tropics, for example, the dominant mechanism is deep moist convection, which supplies water vapor and ice for the formation of upper troposphere cirrus clouds and vents boundary layer water vapor that might otherwise form low-level stratus clouds. A simple estimate of the competing effects of boundary layer humidity and tropospheric lapse rate on convective stability and penetration depth (DelGenio, 1993) suggests that the altitude of tropical cirrus could rise by about 0.3 km (10-15 mb) in 20 years, given a 0.7°C surface warming. In midlatitudes, cloud height variations may be controlled additionally by changes in the strength and vertical scale of baroclinic waves. The change of cloud top level (and thus temperature) required to cause a change of 0.25 W/m^2 of the net radiative flux at the top of the atmosphere, everything else held constant, is about 5 mb (Table 4.1).

Cloud optical thickness. Cloud optical thickness (τ) may be affected both by natural (i.e., thermodynamic and dynamic) and anthropogenic influences. Somerville and Remer (1984) used aircraft liquid water observations over the former Soviet Union to argue that low cloud optical thickness should increase by 4-5% per degree of temperature change. Theoretical arguments based on condensation in a lifted air parcel yield a similar result (Betts and Harshvardhan, 1987). Satellite data for the current climate confirm this finding over cold land areas, but suggest that at warm temperatures and especially over oceans, the optical thickness of low clouds may instead decrease with temperature, by as much as 10% per degree of warming (Tselioudis *et al.*, 1992). Thus, over 20 years with 0.7°C of surface

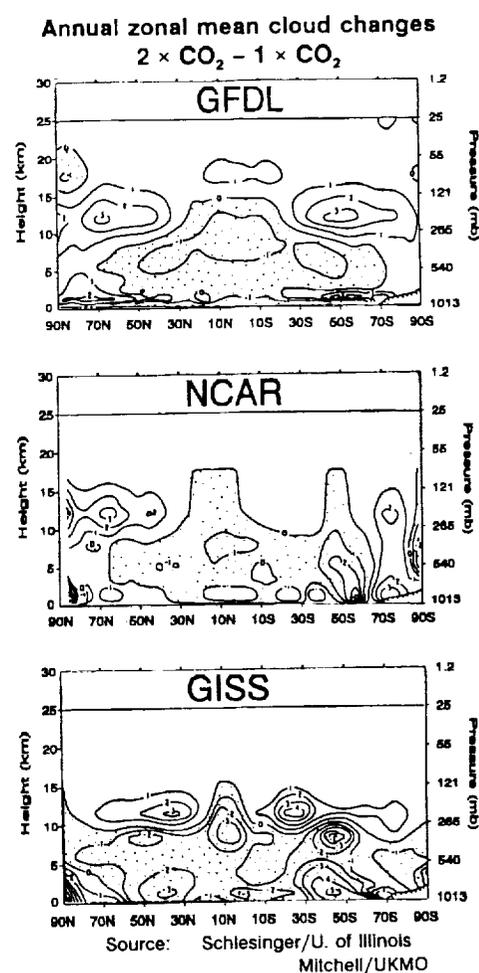


Fig. 3.7. Annual zonal mean cloud changes in equilibrium doubled CO_2 experiments with three GCMs (Schlesinger and Mitchell, 1987).

warming, a typical low cloud with $\tau = 10$ might experience an optical thickness change of about ± 0.5 . If thin cirrus ($\tau \approx 1$) have similar temperature dependence, as suggested by the observations of Platt and Harshvardhan (1988), a much smaller change ($|\tau| < 0.1$) would be projected for that cloud type.

Another mechanism for changing cloud optical thickness is increasing aerosols, which may provide additional cloud condensation nuclei (CCN) for cloud droplet formation, especially over the remote oceans where droplet formation is most limited by the availability of nucleation sites. The effects are twofold. Increasing aerosols may translate into increasing droplet concentration and therefore decreasing droplet size, directly affecting cloud reflectivity (Twomey *et al.*, 1984). For example, if cloud liquid water content remains constant and if the fractional increase in droplet concentration is 70% as large as the increase in aerosol concentration (Kaufman *et al.*, 1991), the 50% regional increase in anthropogenic aerosols discussed above would imply a low cloud optical thickness increase of $\Delta\tau \approx 1$. Furthermore, smaller droplets precipitate less readily, suppressing an important sink of cloud water and thus further increasing cloud optical thickness (Albrecht, 1989). Where these effects occur, relative to the thermodynamic/dynamic controls mentioned previously, will influence the magnitude of the optical thickness changes. Quantitative analysis of the role of cloud optical thickness changes will require both global monitoring and in situ process studies.

Cloud particle size. Changes of cloud particle size are intimately involved in most mechanisms for change of cloud optical thickness. Although it is the change of optical thickness which is the immediate "cause" of a change of radiative balance, and thus of the climate forcing or feedback, it is important to measure the change of cloud microphysics. It is only with such knowledge that we are likely to obtain an understanding of the causes of any long-term changes of cloud radiative properties which affect climate sensitivity.

Cloud particle size changes are the result of the competing influences of changes in cloud water content and droplet concentration. In the absence of aerosol impacts, and ignoring sinks of cloud water such as precipitation and entrainment of clear air, the temperature dependence of adiabatic liquid water content (Betts and Harshvardhan, 1987) implies an increase in effective radius of only about $0.1 \mu\text{m}$ over 20 years. On the other hand, for a 50% regional increase in tropospheric aerosols, effective radius would be expected to decrease by approximately $1 \mu\text{m}$. Size changes that large have been detected in ship tracks (Radke *et al.*, 1989) and between land and ocean clouds and northern and southern hemisphere clouds (Han, 1992). Determination of the climatic significance of this mechanism for cloud particle size change requires long-term global observations.

Radiative Impacts

The plausible changes over a 20 year period of the different climate forcing and feedback parameters discussed above can be readily converted to an approximate radiative flux change at the top of the atmosphere, all other factors being held fixed. The results of such computations are shown in the third column of Table 3.1, based on a radiative model employing the global datasets of the ISCCP project. The flux changes range from a few tenths of a W/m^2 to several W/m^2 . These fluxes define the minimum accuracies that would be required for a global monitoring system. It is apparent that many of these fluxes are comparable in magnitude to the approximate $1 \text{ W}/\text{m}^2$ climate forcing which is anticipated to occur in the next 20 years due to continued increases of the homogeneously mixed greenhouse gases, CO_2 , CFCs, CH_4 and N_2O (IPCC, 1992; Hansen *et al.*, 1988; Ramanathan *et al.*, 1985). The regional cloud changes are expected to be reduced on global average.

Ideally, a monitoring system for climate forcings and feedbacks would be capable not only of detecting changes of the magnitudes indicated in the first column of Table 3.1, but would measure any changes capable of yielding a significant forcing or feedback. We define a significant long-term global mean flux change as $0.25 \text{ W}/\text{m}^2$ or greater, based on the $1 \text{ W}/\text{m}^2$ forcing due to anticipated

TABLE 3.1. Effect of anticipated parameter changes on radiative balance. Summary of anticipated or plausible changes of radiative quantities over a 20 year period (second column) as discussed in the text. The corresponding change in the net radiative flux at the top of the atmosphere is given in the third column, as estimated with a radiative model employing the global datasets of the ISCCP project.

Forcing or Feedback	Anticipated Change of Quantity in 20 Years	Corresponding Δ Flux at TOA (W/m^2)
Ozone	$\frac{\Delta O_3}{O_3} =$ several percent or more	Latitude and Height-dependent
Tropospheric aerosol	$\Delta \tau = 0.04$	-1.0
Stratospheric H ₂ O	$\frac{\Delta q}{q} = 0.3$	+0.3
Surface albedo	$\Delta A_g = 0.01$ (land)	-0.4
Tropospheric H ₂ O upper lower	$\frac{\Delta q}{q} = \begin{cases} .10 \\ .04 \end{cases}$	+1.1 +0.5
Cloud cover cirrus stratus	$\Delta C = \begin{cases} 0.03 \text{ (regional)} \\ 0.03 \text{ (regional)} \end{cases}$	+2.0 -3.0
Cloud top pressure	$\Delta p = -12$ mb	+0.6
Cloud optical thickness cirrus stratus	$\Delta \tau = \begin{cases} 0.1 \\ 1 \end{cases}$ (regional)	+1.4 -3.8
Cloud particle size	$\Delta r = -1 \mu m$ (regional)	-1.4

increases of greenhouse gases in the next 20 years. The constituent changes required to yield such flux changes are considered in Section 7 (Table 7.4). Many of these physical parameter changes are quite small. Nevertheless, we find that the potential exists for long-term monitoring of the climate forcings and feedbacks to precisions close to or exceeding even these more difficult requirements.

4. Summary of Science Overview Session

Peter Stone, Massachusetts Institute of Technology

The Workshop's first session was devoted to an overview of the science of long-term global change, and what type of observations are needed to help understand how the climate system works, what changes are taking place, and what is causing them. Although the workshop's principal objective concerned the global thermal energy cycle, the presentations in the first session focused on understanding both the system's heat and moisture budgets. A starting point for the discussions was provided by the summary of important climate parameters (Table S.1), which had been presented by J. Hansen in his opening remarks for the workshop. Several speakers emphasized the importance of parameters not included in Table S.1, for the purpose of understanding climate change.

J. Mahlman (NOAA/GFDL) opened the session with a discussion of climate monitoring issues from a modeling perspective, as summarized in his essay (Section 1). Mahlman argued convincingly that in the near future advances in our understanding were most likely to come through a synthesis of (incomplete) observations, theory, and modeling.

J. Hansen (NASA/GISS) pointed to uncertainties in our understanding of climate forcings and feedbacks, especially our lack of knowledge about the forcing associated with changes in atmospheric aerosols, the ozone profile, and stratospheric water vapor, and our ignorance about the feedbacks associated with clouds and upper tropospheric water vapor. There was widespread agreement that accurate monitoring of these quantities would provide valuable checks on our climate modeling capabilities, and significantly enhance our understanding of global scale climate sensitivity.

E. Sarachik (University of Washington) noted that understanding the ocean component of the climate system requires a knowledge of all the surface fluxes between the atmosphere and oceans, i.e., momentum, sensible heat, moisture, radiation, and trace gases. K. Trenberth (NCAR) noted the importance of dynamical fluxes of heat and moisture and pointed out that to understand the global energy cycle, one would like to measure *all* the components and fluxes. He also suggested that our knowledge of atmospheric transports could be improved by re-analyzing archived data. T. Karl (NOAA/NCDC) suggested that ground-based measurements of global temperatures could be greatly improved by standardizing all aspects of the observations and analysis, and by optimizing the station network.

A. DelGenio (NASA/GISS) made estimates of the magnitudes of changes of climate forcings and feedbacks that might occur over a twenty-year period, and that we would like to measure. Many of them are inherently very small. Some examples are a global mean surface temperature increase as much as 0.6-0.7 K, ozone changes ~10%, upper tropospheric water vapor changes $\sim 10^{-3}$ g/kg, and global cloud cover changes of the order of 1%. Many speakers pointed out that achieving the required degree of accuracy is often very difficult because many climate parameters have a high degree of spatial and temporal variability, a subject addressed quantitatively later in the workshop. There was general agreement that to obtain data useful for climate it is essential that the measurements be carried out continuously for decades, that the instruments be accurately and consistently calibrated, and that diurnal variations be resolved.

At the same time it was generally recognized that not all the desired measurements would or could be made in the foreseeable future. Examples of measurements that are unlikely to be made are measurements of changes in turbulent surface fluxes of heat and moisture, changes in the structure of the deep oceans, changes in the dynamical transports in the atmosphere and oceans, and changes in the net radiative forcing of the global climate system. However, it was agreed that accurate monitoring of changes of each of the individual global climate forcings and feedbacks in Table S.1 would provide a valuable constraint on interpretation of future climate change.

5. Summary of Session on Existing Monitoring

Richard Somerville, Scripps Institution of Oceanography

A substantial amount of data on global climate forcings and feedbacks is already being obtained. Although many of the measurement systems were not intended for long-term climate monitoring purposes, they provide valuable experience and lessons, as well as datasets. The workshop presentations on existing monitoring are summarized here.

Forcing and Feedback Variables from Operational Satellites. A. Gruber (NOAA/NESDIS) discussed how remote sensing data from observational meteorological satellites can contribute to monitoring climate forcing and feedback variables. The operational instruments include AVHRR, TOVS, SBUV, GOES VAS and SSM/I. As one spectacular example of the utility of these measurements, the AVHRR aboard the NOAA-11 satellite measured the changes in stratospheric aerosol optical thickness following the June 1991 eruption of Mt. Pinatubo. The satellite radiances at 0.6 μm wavelength showed the volcanic cloud encircling the earth in three weeks and gradually spreading into higher latitudes from its origin in the tropics. Preliminary estimates, based on the AVHRR data, were that the globally averaged net radiation at the top of the atmosphere might be reduced by 2.5 W/m^2 over two to four years, thus providing climate modelers with a potentially challenging natural validation experiment.

The TOVS infrared observations of total column ozone have been invaluable in providing independent measurements which complement the ultraviolet data from other sensors. Because the NOAA instruments overlapped for more than a year in 1985-86 with the earlier SBUV data, a consistent and continuous record of total ozone exists since the launch of Nimbus-7 in late 1978. Advantages of the TOVS instrument include a day/night capability and in-flight calibration.

Problems encountered in using operational (and many research) satellite instruments to detect long-term change include drift in both observation time-of-day and sensor calibration. Additional anomalous effects can be severe, such as the effect of aerosols on space-based infrared estimates of sea surface temperature. Operational changes from one satellite to its successor can sometimes compromise the integrity of long-term time series. Nevertheless, operational satellite remote sensing has great potential for climate monitoring. One particularly important area is that of determining cloud parameters, such as cloud amount and cloud top pressure, by techniques other than those used by research satellites. It is especially encouraging that a number of operational products should soon be conveniently accessible to the research community in the pre-EOS time frame as Pathfinder datasets. These sets, each more than a decade long, include AVHRR, TOVS, VISSR and VAS.

Satellite Stratospheric Water Vapor Measurements. D. Rind (NASA/GISS) discussed the critical problem of measuring stratospheric water vapor from space. Climate theorists agree that this quantity is among the most important and most poorly known parameters affecting global climate change. The SAGE II instrument, which has been flying since 1984, has produced invaluable data, including the beginnings of a credible global climatology of stratospheric water vapor. Detailed intercomparisons have been carried out between SAGE II and two short-lived space-based sensors, LIMS on Nimbus-7 in 1978-79 and ATMOS on Spacelab 3 in 1985. SAGE II measurements of tropospheric water vapor also compare well with colocated radiosondes as well as with other remote sensing data. The potential of the SAGE II approach to contribute to stratospheric water vapor monitoring is excellent.

The Global Radiosonde Network. W.P. Elliott (NOAA/ARL) summarized the characteristics of the global radiosonde network which are most relevant to climate monitoring. As is well known, a severe limitation of the network as a climate system is the poor geographical distribution of reporting stations. Only portions of North America and the Eurasian land mass are adequately

sampled. Coverage over land in the tropics and the Southern Hemisphere is marginal at best, and all of the world ocean is poorly represented. Worldwide, only about 700 radiosonde stations report regularly, although more stations exist, and some of the 700 stations report several times a day.

Creating a consistent and homogeneous dataset from radiosonde data is a task with many pitfalls. More than 15 different radiosonde instruments are currently in use, although recently two manufacturers (Viz in the United States and Vaisala in Finland) together appear to have about 75% of the market. Interestingly, differences in relative humidity measurements between instruments made by these two companies may be due in large part to analysis software rather than to the sensors themselves.

In the lower troposphere, the better radiosondes can achieve a one-sigma precision of about 0.2°C in temperature and 3.5% in relative humidity. For typical conditions, this implies that the comparable figures for calculated quantities are approximately 1° for dewpoint, 0.5 gm/kg for specific humidity and 5 to 10% for column water vapor or precipitable water. In principle, a "reference radiosonde" could be developed with higher-quality sensors. It would cost more than operational sondes, but could be co-flown with them and used to intercalibrate and compare the heterogeneous population of sondes, both present and past. Such an effort might well be worthwhile, enabling the extraction of uniquely valuable climate data from the long radiosonde record at a relatively modest cost. The process of improving the radiosonde is a continuing one for the operational services, but it introduces sources of bias into the climate record, and it is critical that these be recognized and taken into account.

Analyzing Regional Climate Using Satellite Imagery. R. Rabin (NOAA/ERL/NSSL) presented a case study carried out by himself and several colleagues (C. Hayden, G. Wade, and L. McMurdie) involving analysis of the atmosphere over the Gulf of Mexico, with emphasis on SSM/I and VAS measurements of total precipitable water and SSM/I measurements of surface wind speed. These satellite remote sensing data, in conjunction with a high-resolution numerical weather prediction model, made it possible to construct a consistent four-dimensional moisture budget for the region.

Sampling Networks for Measuring Aerosol Species. J. Prospero (University of Miami) presented a description of aerosol sampling network operated by the University of Miami. The purpose of this network is to develop a chemical climatology of the major aerosol species. The principal species include sulfate, methanesulfonate, nitrate, ammonia, sodium, and minerals. The long-term goal of the program is to characterize the distribution of these species in the atmosphere over the ocean and to understand the factors that control aerosol concentration, i.e., sources, transport and removal. The experimental strategy for the network includes establishing stations on the coasts of islands and continents in the major ocean regions, with continuously operating instruments. The samples are analyzed in Miami. In addition to climatological sampling, intensive experiments are carried out to address questions of aerosol size, gas-aerosol relationships, and synoptic issues. Results were shown from the Pacific, the Atlantic, and the Antarctic.

Measurements of Condensation Nuclei. J. Gras (CSIRO/DAR) summarized efforts to characterize cloud condensation nuclei in several locations. These include the Antarctic Aerosol Program in the Southern Ocean. Currently, the available network is inadequate to establish a global climatology of condensation nuclei. The Global Atmospheric Watch is a WMO program with eight existing "global" stations, of which five currently have active aerosol programs. Additionally, of 80 "regional" stations, only three have aerosol programs. Because of recent interest in potentially important climate feedback processes involving cloud condensation nuclei, it is hoped that a systematic aerosol measurement program can be established by augmenting this existing network.

Measurements of Clouds and Cloud Properties. W. Rossow (NASA/GISS) surveyed the available sources of observational cloud data, with emphasis on ISCCP. He pointed out that while the satellite remote sensing measurements have the advantage of better spatial and temporal resolution and areal coverage, other approaches have unique advantages of their own. For example, the surface network has the longest record, radiosondes and lidars can provide vertical structure information, and field experiments can elucidate details of physical processes. ISCCP has provided global monitoring of cloud amount, cloud top pressure, and cloud optical thickness. Among the variables which cannot be observed adequately at present, polar cloudiness, thin boundary layer cloudiness and cirrus properties are among the most important. Cirrus clouds are emerging as potentially key elements in the climate puzzle, and future efforts should be directed at measuring quantities such as the diurnal cycle of thin cirrus, the frequency of simultaneous occurrence of cirrus and low clouds, and the microphysical properties of ice clouds.

The Baseline Surface Radiation Network. R. Schiffer (NASA Headquarters) outlined the mission of a baseline surface radiation network. This network is intended to monitor long-term trends in surface radiation fluxes, to validate satellite measurements, and ultimately to lead to an improved understanding of the effects of clouds, water vapor and aerosols on the planetary radiation balance. Estimated measurement accuracies for the major components of the surface radiation budget range between 10 and 30 W/m² at present, and it is hoped that these figures will be reduced to around 5 W/m² in about 5 years.

6. Summary of Session on Proposed Monitoring

Marvin Geller, State University of New York (Stony Brook)

A considerable number of satellite measurements of the climate system are planned for the remainder of this century and the beginnings of the next, as well as some complementary non-space measurements. Presentations were made on several of these, as summarized here.

EOS. J. Dozier (University of California, Santa Barbara), Senior EOS Project Scientist, gave an update on NASA's Planned Earth Observation System (EOS) in the context of planned future space observations of the Earth system. EOS is clearly the planned centerpiece of NASA's Mission to Planet Earth. Dozier's presentation outlined some of the recent changes in EOS. These included a total budget reduction of about 35%, from \$17B to \$11B, a change in implementation plans moving toward a greater number of smaller spacecraft rather than the previous concept of large platforms, and finally a reduction in instrumentation to be flown that reflects a narrowing in the scientific objectives. The first scientific priority will be on clouds, radiation, water vapor, and precipitation. Some of the EOS instruments are on planned flights and others are looking for flights of opportunity. One casualty of the budget reduction was the plan for EOS "hot spares", implying the possibility of data gaps in the event of instrument or spacecraft failure. Much of the EOS data will be obtained at very high spatial resolution, which will be valuable for studies of climate processes. The first EOS launch is planned for 1998.

NOAA Monitoring. L. Stowe (NOAA/NESDIS) presented NOAA's plans for monitoring the climate system. Improved versions of some of today's instruments will be flown. For instance, more channels are to be added to the AVHRR. Changes are also to be made in the infrared sounders and microwave sounders. In particular, the microwave sounding capability will be enhanced to measure more vertical levels and the water vapor profile. NOAA is also looking at some of the EOS instruments to possibly evolve into operational implementation.

Solar Irradiance. J. Lean (NRL) indicated that changes in the total solar irradiance and/or spectral irradiance can be of great importance to climate change. In light of this, she discussed the history of satellite measurements of total solar irradiance as well as solar spectral irradiance. She reminded us that recent satellite observations have clearly indicated the existence of both short and long time scale changes in total irradiance that are related to solar activity. The situation for spectral irradiance is different in that changes on short time scales are clear but changes on long time scales are not so well measured due to problems in calibration and continuity of measurement. Lean showed solar irradiance trends of the past decade measured by several instruments, emphasizing the differences in absolute irradiance among even the best calibrated instruments, implying the need for overlapping data from successive instruments if long-term trends are to be monitored. She emphasized that there are as yet no firm plans for long-term solar monitoring, despite the widely perceived potential importance of the sun in driving the earth's climate. Lean also stressed the important complementary role of ground-based solar observations.

Tropospheric Aerosols. Recently, a great deal of attention has been focused on the role of tropospheric aerosols in the context of climate changes. It has been suggested that while anthropogenic activities tend to lead toward global warming through enhancing the amount of CO₂ and other greenhouse gases, there is also the counterbalancing effect of producing more tropospheric aerosols through sulfur emissions. S. Schwartz (Brookhaven National Laboratories) proposed a network for monitoring aerosols concentrations and properties. Because of the spatial heterogeneity of aerosols, ground-based stations should be supplemented by satellite monitoring, but the satellite data will need to be much more accurate than current operational products if they are to be substantially useful.

ARM. G. Stokes (Pacific Northwest Laboratory) spoke about the planned Atmospheric Radiation Measurement (ARM) program that is being implemented by the U.S. Department of Energy (DOE). The ARM mission is aimed at improving our knowledge of radiative transfer and the role of clouds, with an emphasis on process studies. ARM includes measurements from ground-based facilities, remotely piloted aircraft, and satellites.

ARMSat. Finally, J. Vitko (Sandia National Laboratory) discussed DOE's planned ARMSat program. He indicated that DOE sees ARMSat as using DOE experience in space science and engineering to build small spacecraft that obtain measurements that are important for the understanding of clouds, radiation and climate changes.

In summary, those spacecraft and surface observations that are planned for the next several years will obtain very interesting data for the study of climate change. These planned programs do not mitigate the need for the long-term monitoring by the proposed Climsat program, however.